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Urban Tunnel Systems for Conveyance and Storage of Storm- and Wastewater: Features, Classification, and Modelling

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Abstract: Tunnels have been integrated in many urban drainage systems to assist in preventing combined sewer overflows and flooding. Despite a wide range of designs, these structures share a common defining feature: conveying and storing large quantities of water. Urban tunnel systems can then be classified based on the type of water conveyed (wastewater, stormwater, or combined). The analysis of a representative sample of case studies shows how tunnels have been adapted to different economic, demographic, and climatic contexts. Across different designs, the management of existing urban tunnels can be optimized with intelligent monitoring and control strategies. These require models capable of providing real-time system-wide state estimates and reliable forecasts.

Keywords: deep tunnel; drainage; CSO; real time control; data assimilation.

1. INTRODUCTION

Tunnels have been integrated in many urban drainage systems as an effective solution to combined sewer overflow (CSO) and flooding. The substantial growth of the urban population, the greater proportion of hard surfacing, and the higher frequency of intense rain events have drastically increased flows in the drainage network. When the design capacity is exceeded, excess water overflows to the natural recipients or backs up into the drainage system, causing street flooding. Responses to this problem typically include a combination of green (reducing or delaying runoff at source) and grey (diverting and temporarily storing excess water) solutions. The choice between green or grey strategies is the outcome of complex political, environmental, technical, economic and social factors (Dolowitz et al., 2018). Tunnels fall into the second category, as they are used to store water during peak flows and convey it to treatment or discharge. Although originally designed specifically for control of pollution and flooding from combined sewers (Koelzer et al., 1969), urban tunnels have also been adopted to convey and store source separated stormwater or wastewater. The variety of uses and designs results in a plethora of expressions referring to similar systems (e.g. deep storage tunnel for combined stormwater and sewage vs. CSO tunnel).

Real time control (RTC) has the potential of turning drainage systems from passive transportation infrastructure into “smart” storage devices, thus reducing the need for investment in new infrastructure (Eggimann et al., 2017). Control decisions can be based not only on the monitored state of the system but also on forecasts, technique known as model predictive control (MPC). Urban tunnels are particularly suitable for testing and implementing MPC, due to the high degree of controllability and the potential economic benefits (e.g. reduction of pumps’ energy consumption). However, there is a need for fast and accurate models, and methods for assimilating on-line observations (Lund et al., 2018).

As a starting point for future research on real time management of urban tunnel systems, this work analyses a representative sample of case studies with the aim of i) defining common features of tunnel systems, ii) suggesting a classification, and iii) identifying opportunities for enhancements in modelling and control.

2. MATERIALS AND METHODS

Terminology. The word tunnel refers to “an artificial underground passage”, and is associated with a category of construction techniques rather than a specific use. The construction method depends on the ground material and conditions, and can be highly automated using tunnel boring machines, with a consequent reduction in costs. A major advantage of bored tunnels is the minimal disruption generated at the surface level during construction, which is particularly convenient in existing urban areas. Specifically, water tunnels are used as underground channels to transport large quantities of water, either for supply or disposal. When considering also their auxiliary infrastructure, urban tunnels for water disposal can be regarded as a sub-system of the larger urban drainage system. Hereafter the word tunnel refers to a tunnel system for drainage of water in urban areas.

Case studies. The selected case studies (Table 1) are meant to represent the variety of catchments in which tunnels have been built or planned around the world. Many factors are expected to influence choices in the planning and design of a tunnel. First of all, tunnels need to be cost-effective, meaning that the high initial investment has a short enough return period. This requires a robust economy and/or a large number of users served, conditions often satisfied in metropolitan areas. Moreover, the extent of the supplementary storage capacity provided by the tunnels should be defined with regards to the actual and estimated inflows in the drainage network, in terms of magnitude, frequency and spatial distribution. For simplicity, three key parameters are respectively used for the economic, demographic, and climatic characterization of the tunnel catchment: per capita gross domestic product (GDP) for year 2012 (OECD, 2012), density of population for year 2014 (OECD, 2012), and average annual precipitation (retrieved from the national meteorological institutes). To compare tunnels of different typology three key design parameters are used: cumulative length of the tunnels belonging to the same system, maximum internal diameter, and maximum depth.

Table 1. Overview of case studies, including urban area served by the tunnel, name of the project, year of start of operations (a planned start is mark with *), and key benefit (as stated by the water utility companies).

Location	Project name	Start of operations	Key benefit
Abu Dhabi, UAE	*Strategic Tunnel Enhancement Programme*[1]	2017	Greywater reuse
Chicago, IL, USA	*Tunnel and Reservoir Plan*[2]	1985	Pollution prevention
Copenhagen, DK	*Østerbro Stormwater Tunnel*[3]	2017	Couldburst relief
London, UK	*Thames Tideway Tunnel*[4]	2023*	CSO reduction
Mexico City, MX	*Tunnel Emisor Oriente*[5]	2018*	Flood prevention
Singapore, SG	*Deep Tunnel Sewerage System*[6]	2008	Land use optimisation
Kuala Lumpur, MY	*Stormwater Management And Road Tunnel*[7]	2007	Multi-functional

[1] https://www.adssc.ae/en-us/Steps/Pages/Snappy.aspx (accessed 12/03/2018)
[2] https://www.mwrd.org/irj/portal/anonymous/tarp (accessed 12/03/2018)
[3] https://www.hofor.dk/pressemeddelse/regnvandstunnel-skal-skybrudssikre-ydre-oesterbro/?hilite=%27Regnvandstunnelen%27 (accessed 12/03/2018)
[4] https://www.tideway.london/ (accessed 12/03/2018)
[5] http://201.116.60.81/sustentabilidadhidricadelValledeMexico/TunelEmisorOriente.aspx (accessed 12/03/2018)
[6] https://www.pub.gov.sg/dtss (accessed 12/03/2018)
[7] http://smarttunnel.com.my/smart/what-is-smart/ (accessed 12/03/2018)

3. RESULTS AND DISCUSSION

Features. The wide range in the design parameters of the selected case studies (Table 2) reflects the flexibility of tunnels in adapting to different contexts and purposes. The tunnel system in Chicago is a pioneering project conceived in the late 60s to intercept and store combined sewer overflows in a long network of tunnels and reservoirs, protecting the water quality in Lake Michigan, which is used for water supply. London's tunnels will serve a similar purpose and are being built under the Thames River, to optimise combined sewer overflow interception. In spite of a less wealthy economy, Mexican authorities opted for a deep tunnel system to prevent flooding in the densely populated valley of the Mexico City area, which currently hosts around 20 million inhabitants. The tunnels in Abu Dhabi and Singapore are both part of a separate sewer system, and are designed for the centralised drainage of sewage, although built in areas with significantly different amounts of precipitation (arid vs. tropical). The relatively small stormwater tunnel in Copenhagen is an example of how these structures can also respond to local needs, instead of serving the whole urban catchment. Finally, the tunnel in Kuala Lumpur is used both for vehicular traffic and stormwater diversion, with the dual purpose of traffic congestion relief and flood prevention. In all cases, tunnels are designed to intercept water by gravity and convey it to final treatment and/or discharge, while the large internal diameter allows for temporary storage. The connection to the existing drainage network upstream and the downstream recipient requires the construction of some auxiliary infrastructure, which typically includes i) a series of link sewers and/or interception chambers, ii) dropshafts, usually divided in two parts to allow air to exit as water enters the system at high velocity, iii) pumping stations, located at the termination of the tunnels, in addition to iv) inspection shafts and v) a network of sensors, for monitoring and maintenance purposes.

Classification. The analysis of the case studies doesn't provide evidence that the design criteria are predominantly influenced by any of the catchment parameters investigated. It is, rather, a combination of these (and other) factors that determines the specific design requirements of a tunnel. Therefore, we suggest a classification of tunnels based on the type of water that needs to be conveyed: wastewater, stormwater, or a mixture of the two (combined). Wastewater tunnels enable a centralised control of the drainage network, and allow to decommission intermediate pumping stations, freeing up valuable land. Stormwater tunnels protect urban areas from the risk of flooding, draining away stormwater during intense rain events. Finally, combined tunnels prevent pollution of the receiving water bodies, intercepting and storing combined sewer overflows (CSOs).

Modelling. Many numerical models exist that are capable of simulating the hydraulic behaviour of the drainage networks, and additional models have been developed to specifically represent tunnel hydraulics (Morales et al., 2017). These can range from a steady-state conveyance model to an unsteady, mixed-flow (air mixed with water) model, to 3-dimensional computation flow dynamics (CFD) models of selected structures. Models can support control strategies aimed at reducing the high operational costs and preventing adverse phenomena, e.g. excessive sedimentation, unwanted chemical and biological reactions, and problems related to rapid filling. When used for control purposes, however, the models need to be kept in touch with reality based on observations from the system and furthermore the models need to provide quantitative uncertainty estimates. This might be accomplished using e.g. ensemble based data assimilation methods, but this is research for the near future.

Table 2. Comparison of selected case studies based on catchment parameters (per capita gross domestic margin (GDP), density of population, and average annual precipitation), and design parameters (cumulative length, maximum internal diameter, and maximum depth).

TUNNEL		CATCHMENT			DESIGN		
Location	Typology	Per cap. GDP (USD)	Population density ($1/km^2$)	Annual precip. (mm)	Length (km)	Max diameter (m)	Max depth (m)
Abu Dhabi	wastewater	95,000	1,200	57.1	41	7	85
Chicago	combined	58,288	510	937	176	10	110
Copenhagen	stormwater	49,019	496	523	0.6	2.5	13
London	combined	54,382	1792	602	25	7.2	70
Mexico City	combined	20,960	4000	846	62	7.5	200
Singapore	wastewater	52,962	7807	2343	78	6	50
Kuala Lumpur	stormwater (+traffic)	19,258	6890	2628	9.8	11.8	16

CONCLUSIONS

Urban tunnel systems have the potential of solving various problems in urban water management, and their benefits can be maximized by implementing intelligent control strategies. The scientific and technical literature refers to urban tunnel systems with a wide range of terms, and this reflects the variety of contexts in which they are built, and the consequent design criteria. However, their defining feature is the ability to convey and store large quantities of water in urban areas, with minimal disruption at the surface level and attractive cost-benefit ratios. “Urban tunnel systems” encompasses the whole category, with a suggested classification based on the type of water conveyed (wastewater, stormwater, or combined).

Excavating large tunnels to expand the storage capacity of the drainage network is not enough to future-proof urban drainage systems, if this supplementary volume is not adequately monitored and controlled. Data assimilation techniques pave the way for optimizing the management and control of both existing and newly built tunnels, being capable of providing real-time system-wide estimates of state variables and reliable forecasts. However, for a successful implementation, these tools need to be adjusted to the specific needs of urban tunnel systems, and be transferable across a range of different typologies and designs.

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